(HEP-PH/0007NNN, 31. JULY 2000)

IMPLICATIONS OF A LOW $\sin 2\beta$: A STRATEGY FOR EXPLORING NEW FLAVOR PHYSICS

ALEXANDER L. KAGAN

Department of Physics, University of Cincinnati
Cincinnati, OH 45221, USA

MATTHIAS NEUBERT

Newman Laboratory of Nuclear Studies, Cornell University
Ithaca, NY 14853, USA

We explore the would-be consequences of a low value of the CP-violating phase $\sin 2\beta_{\psi K}$. The importance of a reference triangle obtained from measurements that are independent of B–$\bar{B}$ and K–$\bar{K}$ mixing is stressed. It can be used to extract separately potential New Physics contributions to mixing in the B_d, B_s and K systems. We discuss several constructions of this triangle, which will be feasible in the near future. The discrete ambiguity is at most two-fold and eventually can be completely removed. Simultaneously, it will be possible to probe for New Physics in loop-dominated rare decays.

1 Introduction

One of the highlights of the ongoing ICHEP2000 Conference in Osaka has been the presentation of first results on CP violation in B_d–$\bar{B}_d$ mixing by the BaBar and Belle Collaborations [1]. The reported values obtained from the time-dependent CP asymmetry in $B \to J/\psi\, K_S$ decays,

$$\sin 2\beta_{\psi K} = \begin{cases} 0.12 \pm 0.37 \pm 0.09\,; & \text{BaBar}, \\ 0.45\,^{+0.43+0.07}_{-0.44-0.09}\,; & \text{Belle}, \end{cases} \tag{1}$$

are smaller than the previous best measurement $\sin 2\beta_{\psi K} = 0.79^{+0.41}_{-0.44}$ by the CDF Collaboration [2]. They are also smaller than the value $\sin 2\beta = 0.75 \pm 0.06$ obtained from a recent global analysis of the unitarity triangle [3]. Although there is at present no statistically significant discrepancy, it is interesting to explore the implications of a measurement of $\sin 2\beta_{\psi K}$ that would be inconsistent with the results of the global analysis. Under the assumption that there is no CP-violating New Physics in $b \to c\bar{c}s$ transitions (which is supported by the strong experimental bound on direct CP violation in $B^\pm \to J/\psi\, K^\pm$ decays reported by the CLEO Collaboration [4]) this would imply the existence of New Physics in B_d–$\bar{B}_d$ mixing. (New Physics in K–$\bar{K}$ mixing could not account for such a discrepancy, because of the minor impact of $|\epsilon_K|$ on the global analysis.) The measured phase $2\beta_{\psi K}$ would then be the B_d–$\bar{B}_d$ mixing phase $2\phi_d$, which would differ from the CKM phase 2β because of New Physics. In such an event, it is likely that New Physics would also play a role in B_s–$\bar{B}_s$ and K-$\bar{K}$ mixing.

The purpose of this Letter is to point out a strategy which provides a systematic exploration of the new flavor physics in this case. This strategy is different from the conventional route pursued at the B factories, in which the main focus is on measurements that are sensitive to B–$\bar{B}$ mixing, mainly because CP violation in the interference of mixing and decay can sometimes be interpreted without encountering large hadronic uncertainties. If there is New Physics in mixing, then the standard triangle obtained by combining information on $|V_{ub}|$ from semileptonic B decay, $\Delta m_{d,s}$ from $B_{d,s}$–$\bar{B}_{d,s}$ mixing, and $|\epsilon_K|$ from K–$\bar{K}$ mixing does not agree with the true CKM triangle, and forcing it to close (as is done in the standard

analysis) gives wrong results for the angles $\gamma = \arg(V_{ub}^*)$ and $\beta = -\arg(V_{td})$. (We use the standard phase conventions; otherwise $\gamma = \arg[-(V_{ub}^* V_{ud})/(V_{cb}^* V_{cd})]$ and $\beta = \arg[(V_{tb}^* V_{td})/(V_{cb}^* V_{cd})]$.)

In the absence of a reliable way to measure the magnitude and phase of V_{td} in B decays, it is important to base studies of the CKM matrix on a *reference triangle* obtained exclusively from measurements independent of particle–antiparticle mixing [5,6,7,8]. In the B system, this triangle is constructed from the measurement of the magnitude and phase of V_{ub}. (The use of $\gamma = \arg(V_{ub}^*)$ replaces the use of $|V_{td}|$, determined from B–$\bar{B}$ mixing, in the standard analysis.) Separate comparisons of particle–antiparticle mixing measurements in the B_d, B_s and K systems with information obtained from the reference triangle will allow extraction of the magnitude and phase of New Physics contributions to the mixing amplitudes. At a later stage, comparison of different reference triangle constructions can provide information about potential New Physics effects in the decay amplitudes, not related to mixing.

We stress that the reference triangle approach should be pursued regardless of whether or not the $\sin 2\beta_{\psi K}$ measurements are consistent with the global analysis of the unitarity triangle. Agreement within errors could be accidental and would not exclude the possibility of large New Physics contributions in B_d–$\bar{B}_d$ mixing. Proposals similar in spirit to ours have been discussed in the past. However, their feasibility is limited by their reliance on methods for extracting γ that are extremely difficult, and are plagued by multiple discrete ambiguities [5,7]. In the past two years, however, several strategies have been proposed that will allow a determination of γ in the near future, without discrete ambiguities and with controlled theoretical uncertainties.

Our analysis is based on the following standard assumptions, which hold true for a vast class of extensions of the Standard Model (for a discussion, see e.g. Ref. [8]):

i) The determination of the CKM elements $|V_{us}|$, $|V_{cb}|$ and $|V_{ub}|$ from semileptonic decays is not affected by New Physics.

ii) The 3-generation CKM matrix is unitary.

iii) There are no (or negligibly small) New Physics effects in decays which in the Standard Model are dominated by tree topologies.

An experimental test for non-standard contributions in the semileptonic $b \to u\,l\,\nu$ transition could be performed by comparing the values of $|V_{ub}|$ extracted from the exclusive $B \to \pi\,l\,\nu$ and $B \to \rho\,l\,\nu$ decays, and the inclusive $B \to X_u\,l\,\nu$ decays. (An analogous test for $b \to c\,l\,\nu$ decays has been proposed in Ref. [9].) Tests of the unitarity of the CKM matrix will be discussed in Section 4.

2 The reference triangle

Disregarding all information obtained from mixing measurements, not much is known about the Wolfenstein parameters $(\bar{\rho}, \bar{\eta})$ determining the unitarity triangle. The magnitude of $|V_{ub}|$ measured in semileptonic B decay fixes $R_b = |(V_{ub}^* V_{ud})/(V_{cb}^* V_{cd})| = \sqrt{\bar{\rho}^2 + \bar{\eta}^2}$, corresponding to a circle centered at the origin in the $(\bar{\rho}, \bar{\eta})$ plane. At present $|V_{ub}|$ is known with a precision of about 20%. A reduction of the uncertainty to the 10% level appears realistic within a few years. The phase γ defining the orientation of the triangle ($\sin\gamma = \bar{\eta}/R_b$) is currently unknown.

2.1 Reference triangles from B decays

In the very near future, ratios of CP-averaged $B \to \pi K$ and $B \to \pi\pi$ branching ratios can be used to extract $\cos\gamma$ using many different strategies. A method based on flavor symmetries, using little theory input, has been described in [10]. It makes use of two experimentally determined rate ratios (R_* and $\bar{\varepsilon}_{3/2}$) and the theoretical prediction[11] that the relevant strong-interaction phase cannot be very large. Alternatively, it has been argued re-

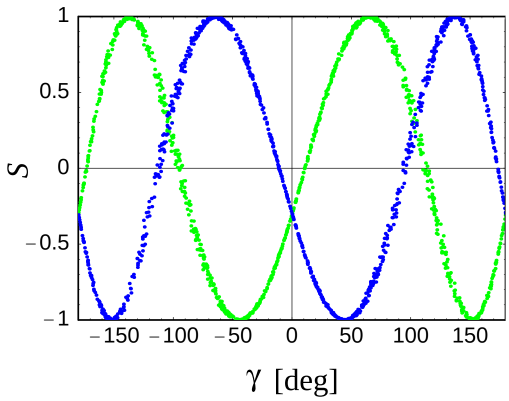

Figure 1. Determination of γ from the mixing-induced CP asymmetry in $B \to \pi^+\pi^-$ decays, assuming $\sin 2\phi_d = 0.3$. The dark band refers to $2\phi_d \simeq 17.5^\circ$, the light one to $2\phi_d = 162.5^\circ$.

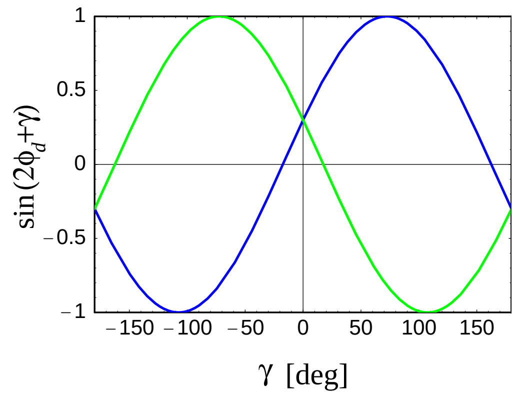

Figure 2. Determination of γ from the measurement of $\sin(2\phi_d+\gamma)$ in $B \to D^{(*)\pm}\pi^\mp$ decays, assuming $\sin 2\phi_d = 0.3$. The dark curve refers to $2\phi_d \simeq 17.5^\circ$, the light one to $2\phi_d = 162.5^\circ$.

cently that in the heavy-quark limit most two-body hadronic B decays admit a model-independent theoretical description based on a QCD factorization formula [11]. Predictions for the $B \to \pi K, \pi\pi$ decay-rate ratios as a function of $\cos\gamma$ have been obtained (including the leading power corrections in $1/m_b$) [12]. The combination of several independent determinations of $\cos\gamma$ from these modes will fix γ, up to a sign ambiguity $\gamma \to -\gamma$, with reasonable precision. (We define all weak phases to lie between -180° and 180°.) We believe that an uncertainty of $\Delta\gamma = 25^\circ$ will be attainable in the near future.

Once the $B^\pm \to (\pi K)^\pm$ and $B^\pm \to \pi^\pm\pi^0$ decay rates are known with higher precision, γ can be determined with minimal theory input (up to discrete ambiguities) using the method of Ref. [13]. Here, in addition to CP-averaged decay rates, information about some direct CP asymmetries is added. Ultimately, this will reduce the theoretical uncertainty to a level of 10° or less. When supplemented with theoretical information on the strong-interaction phase this method can be used to completely eliminate the discrete ambiguities (for a detailed discussion, see Ref. [10]).

The QCD factorization approach can also be used to calculate the penguin-to-tree ratio in $B \to \pi^+\pi^-$ decays, thereby turning a measurement of the mixing-induced CP violation into a determination of γ without the need for an (impractical) isospin analysis [12]. In Figure 1 we show the coefficient S of $-\sin(\Delta m_d\, t)$ in the time-dependent CP asymmetry as a function of γ, assuming $\sin 2\phi_d = 0.3$ for the B–$\bar{B}$ mixing phase measured in $B \to J/\psi\, K_S$. A measurement of $\sin 2\phi_d$ determines the phase $2\phi_d$ up to a two-fold discrete ambiguity, $2\phi_d^{(1)} + 2\phi_d^{(2)} = \pi \bmod 2\pi$. The width of the bands reflects the theoretical uncertainty. The eight-fold ambiguity can be reduced to a four-fold one, in principle, by measuring the direct CP asymmetry in this decay. Alternatively, using a Dalitz-plot analysis of the $B \to \rho\pi$ decay amplitudes one could determine $\sin(2\phi_d + 2\gamma)$ with small hadronic uncertainties [14].

On a much longer time-scale, it will be possible to obtain information on γ (again up to discrete ambiguities) using only decays mediated by tree topologies in the Standard Model. Examples are the determination of $\sin(2\phi_d + \gamma)$ from $B \to D^{(*)\pm}\pi^\mp$ decays [15], and the extraction of γ from $B \to DK$ decays [16]. This last method, in particular, will require very large data samples. Other methods make use of B_s-meson decays accessible at future B factories at hadron colliders [17]. In Figure 2 we show as an example the information obtainable from a determi-

nation of $\sin(2\phi_d + \gamma)$. Combining this with the information derived from a measurement of the $B \to \pi^+\pi^-$ CP asymmetry (see Figure 1), a unique pair of solutions $(\gamma, 2\phi_d^{(1)})$ and $(-\gamma, 2\phi_d^{(2)})$ is obtained. We stress that combining any of the measurements sensitive to B_d–$\bar{B}_d$ mixing described above with a determination of γ (including its sign) from $B \to \pi K$ would remove the discrete ambiguity in the B_d mixing phase $2\phi_d$.

Up to now we have assumed that the various determinations of the reference triangle from B decays are consistent with each other. This assumption will have to be tested as the data become increasingly precise. In Section 4 we will discuss how *differences* between these constructions would provide information about New Physics in B decays rather than B_d–$\bar{B}_d$ mixing.

2.2 Reference triangle from K decays

An independent reference triangle can be constructed from measurements of very rare kaon decays. The branching ratios for the decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ measure $|V_{ts}^* V_{td}|$ and $|\mathrm{Im}(V_{ts}^* V_{td})|$, respectively, and thereby determine $R_t = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}$ and $|\eta|$ independently of K–$\bar{K}$ mixing [18]. This provides a reference triangle up to a four-fold discrete ambiguity. Dedicated experiments would be necessary to measure R_t and $|\eta|$ with useful precision. In Section 4 we will discuss what can be learned from the comparison of the kaon reference triangle with the B-meson triangle(s).

3 Exploring New Physics

Once the reference triangle is known, we can use it to explore New Physics contributions to B–$\bar{B}$ and K–$\bar{K}$ mixing. Measurement of R_b and γ fix the coordinates $\bar{\rho}$ and $\bar{\eta}$, which in turn determine the other side R_t and the true angle β of the reference triangle via

$$R_t = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}\,,$$

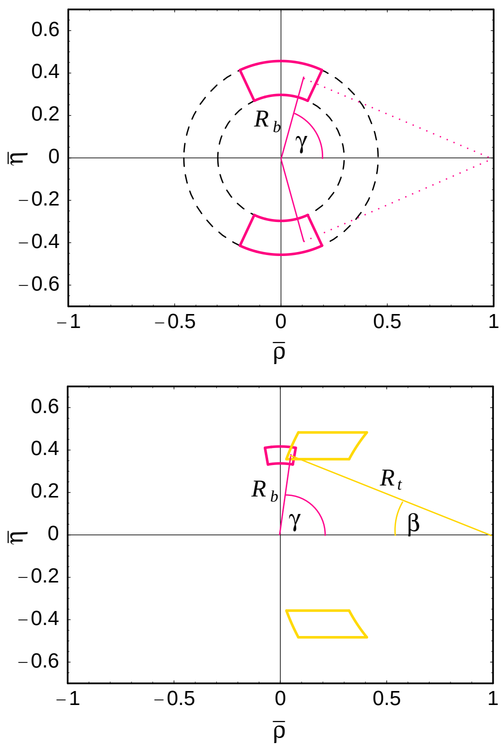

Figure 3. Illustrative examples of reference triangle constructions in the near and long-term future. (a) B-decay triangle with two-fold ambiguity, assuming uncertainties of 20% in $|V_{ub}/V_{cb}|$ and $\pm 25°$ in γ (near-term). The dashed circles correspond to the measurement of $|V_{ub}/V_{cb}|$. (b) B-decay triangle (dark) with no ambiguity, assuming uncertainties of 10% in $|V_{ub}/V_{cb}|$ and $\pm 10°$ in γ, and K-decay triangle (light) with four-fold ambiguity, assuming 15% uncertainties in R_t and $|\eta|$ (long-term). The two solutions for the kaon triangle obtained with $\bar{\rho} \to 2 - \bar{\rho}$ are not shown.

$$\sin\beta = \frac{\bar{\eta}}{R_t}\,, \quad \cos\beta = \frac{1-\bar{\rho}}{R_t}\,. \qquad (2)$$

In Figure 3, we illustrate what the situation may look like both in the near and long-term future. We assume that in the near future γ will be known only up to a sign ambiguity (from measurements of CP-averaged decay rates), which will be resolved after several more years of running at the B factories (when certain CP asymmetries in rare decays will have been measured).

3.1 B_d–$\bar{B}_d$ mixing

We now discuss how one can systematically study New Physics effects in the B_d–$\bar{B}_d$ mix-

ing amplitude M_{12} by confronting measurements of the mass difference $\Delta m_d = 2|M_{12}|$ (or $x_d = \Delta m_d\,\tau_B$) and of the mixing phase $\sin 2\phi_d$ with the reference triangle. Our approach is very similar to the one discussed in Ref. [5]. Using (2) we construct the complex quantity $R_t^2\,e^{-2i\beta}$ with the *true* CKM phase β. Up to a constant C_B, this quantity determines the Standard Model contribution to the mixing amplitude: $M_{12}^{\rm SM} = C_B\,R_t^2\,e^{-2i\beta}$, where [18]

$$C_B = \frac{G_F^2}{12\pi^2}\,\eta_B\,m_B\,m_W^2\,S_0(x_t)\,B_B f_B^2 \simeq 0.24\,\text{ps}^{-1}\times\frac{B_B f_B^2}{(0.2\,\text{GeV})^2}\,. \qquad (3)$$

The main uncertainty in this result comes from the hadronic matrix element parameterized by the product $B_B f_B^2$. It is therefore convenient to focus on the ratio M_{12}/C_B, which in the Standard Model is given only in terms of CKM parameters: $M_{12}^{\rm SM}/C_B = [(1-\bar\rho)^2-\bar\eta^2)] - 2i\bar\eta(1-\bar\rho)$. (If New Physics does not induce operators with non-standard Dirac structure, the ratio M_{12}/C_B remains free of hadronic uncertainties.) The experimental value of the mixing amplitude is given by $M_{12}^{\rm exp}/C_B = (\Delta m_d/2C_B)\,e^{-2i\phi_d}$. If the mixing phase is determined from the $\sin 2\phi_d$ measurement in $B\to J/\psi\,K_S$ decays alone, then $e^{-2i\phi_d}$ has a two-fold discrete ambiguity. In the previous section we have discussed how this ambiguity may eventually be resolved by using data on CP violation in B decays. The difference $M_{12}^{\rm NP} = M_{12}^{\rm exp} - M_{12}^{\rm SM}$ is the New Physics contribution to the mixing amplitude.

In Figure 4 we illustrate this analysis using present-day values of the input parameters from Ref. [3] ($|V_{ub}/V_{cb}| = 0.085\pm 0.018$, $\sqrt{B_B}f_B = (0.21\pm 0.04)\,\text{GeV}$) and the average of the new BaBar and Belle results, $\sin 2\phi_d = 0.26\pm 0.29$. The upper plot shows the allowed regions for the Standard Model contribution to the mixing amplitude as well as for its experimental value, taking into account the two-fold ambiguity in the mixing angle $2\phi_d$. The difference between any point

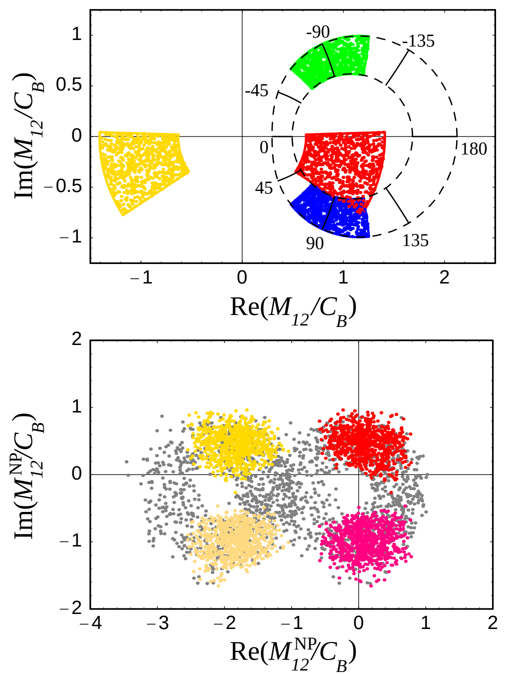

Figure 4. Determination of the B_d–$\bar B_d$ mixing amplitude M_{12} (in units of C_B) in the complex plane, assuming present day uncertainties on the input parameters (see text). (a) Standard Model contribution $M_{12}^{\rm SM}$ (region bounded by the dashed circles) with marks indicating fixed values of γ. The filled regions between the circles correspond to $|\gamma| = (90\pm 25)^\circ$. The experimentally determined regions for M_{12} are shown for $\sin 2\phi_d = 0.26\pm 0.29$, where $2\phi_d \approx 15^\circ$ (middle right) and $2\phi_d \approx 165^\circ$ (left). (b) New Physics contribution $M_{12}^{\rm NP}$ corresponding to the different regions: $(\gamma, 2\phi_d)\approx(90^\circ, 15^\circ)$ (upper right), $(\gamma, 2\phi_d)\approx(-90^\circ, 15^\circ)$ (lower right), $(\gamma, 2\phi_d)\approx(90^\circ, 165^\circ)$ (upper left), $(\gamma, 2\phi_d)\approx(-90^\circ, 165^\circ)$ (lower right). The rings of scatter points correspond to arbitrary γ.

in the Standard Model regions with any point in the data regions defines an allowed vector in the complex $M_{12}^{\rm NP}$ plane. In the lower plot we show the resulting allowed regions for $M_{12}^{\rm NP}$. The origin in this plot corresponds to the Standard Model. We also show the results in the absence of any information on γ. An important message from this plot is that a potentially large New Physics contribution (of order the Standard Model contribution) to the mixing amplitude is allowed by the data in large portions of parameter space. In order to find out whether or not there is indeed such a large contribution it

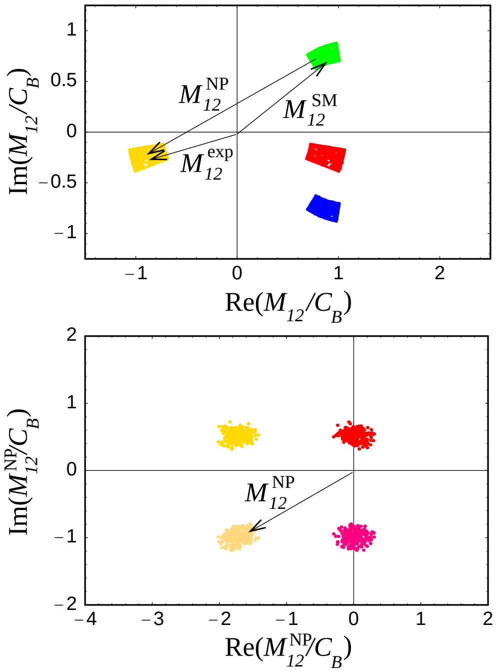

Figure 5. Same as Figure 4, but with smaller uncertainties on input parameters. The arrows indicate the construction of the New Physics contribution as explained in the text.

will be necessary to determine γ and resolve the discrete ambiguity in $2\phi_d$.

Figure 5 illustrates what the situation may look like several years from now. By then the uncertainties in the input parameters will most likely have been reduced significantly, and the mixing angle will have been measured with good precision. For the purpose of illustration we take $|V_{ub}/V_{cb}| = 0.085 \pm 0.009$, $\sqrt{B_B} f_B = (0.21 \pm 0.02)\,\mathrm{GeV}$, and $\sin 2\phi_d = 0.26 \pm 0.10$. Also, the phase γ will have been measured more accurately, perhaps with $\Delta\gamma = 10°$. This would lead to the picture shown in Figure 5(a) and to the allowed regions for New Physics shown in (b). Most importantly, as we have explained, in the long term the discrete ambiguities in both γ and $2\phi_d$ will be removed, so that it would be possible to identify *which one of the four regions* in (b) is realized in nature. At this point, we will have achieved a precise determination of the New Physics contribution to B_d–$\bar{B}_d$ mixing.

3.2 B_s–$\bar{B}_s$ mixing

In the presence of New Physics in B_d–$\bar{B}_d$ mixing, it is very likely that also the B_s–$\bar{B}_s$ mixing amplitude is different from its value in the Standard Model. Therefore, measurements sensitive to this mixing amplitude should not be combined with measurements in the B_d system. Rather, one should probe for New Physics in the B_s system in an independent way. In the Standard Model the assumption of unitarity of the CKM matrix alone fixes the magnitude of $|V_{tb}^* V_{ts}|$ (and hence the Standard Model contribution to Δm_s), and in addition implies that the B_s mixing phase is very small, $\phi_s^{\mathrm{SM}} = O(\lambda^2)$ (with $\lambda \simeq 0.22$ the Wolfenstein parameter). Even at the approved hadron collider experiments BTeV and LHCb it will not be possible to measure this small Standard Model phase. It follows that the complex amplitude $M_{12}^{\mathrm{SM}}(B_s)$ is determined by unitarity and is very nearly real. (In that sense the "B_s reference triangle" is almost degenerate to a line.) Measuring the true values of the mass difference Δm_s and of the mixing phase $2\phi_s$ (e.g., from the time-dependent CP asymmetry in $B_s \to J/\psi\,\phi$ decays), one can then construct the mixing amplitude from $M_{12}(B_s) = (\Delta m_s/2)\,e^{-2i\phi_s}$. The difference $M_{12}^{\mathrm{NP}}(B_s) = M_{12}(B_s) - M_{12}^{\mathrm{SM}}(B_s)$ determines directly the New Physics contribution to B_s–$\bar{B}_s$ mixing.

3.3 K–$\bar{K}$ mixing

The mass difference Δm_K between the neutral kaon mass eigenstates is dominated by long-distance physics and does not admit a clean theoretical interpretation. Therefore, constraints on the CKM matrix from K–$\bar{K}$ mixing are derived only from the CP-violating quantity $|\epsilon_K|$, which (to a very good approximation) is given by $|\epsilon_K| \simeq |\mathrm{Im}[M_{12}(K)]|/(\sqrt{2}\Delta m_K)$. Consequently, one can only derive information on the New Physics contribution to the imaginary part of the mixing amplitude in the kaon system.

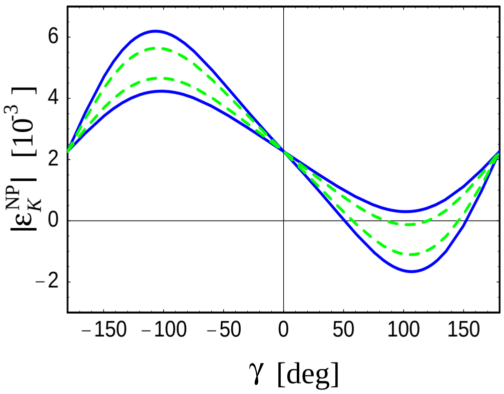

Figure 6. New Physics contribution to $|\epsilon_K|$ in units of 10^{-3}, assuming present day uncertainties (region bounded by dark solid curves, corresponding to $B_K = 0.86 \pm 0.10$, $|V_{ub}/V_{cb}| = 0.085 \pm 0.018$) and future smaller errors (region bounded by light dashed curves, corresponding to $B_K = 0.86 \pm 0.05$, $|V_{ub}/V_{cb}| = 0.085 \pm 0.009$).

The Standard Model contribution to $|\epsilon_K|$ is the product of a function of the Wolfenstein parameters $\bar{\rho}$ and $\bar{\eta}$ with a hadronic matrix element parameterized by the quantity B_K [18]. Once we have determined $\bar{\rho}$ and $\bar{\eta}$ (as a function of γ and R_b) from the reference triangle, we can compute the Standard Model contribution. Subtracting it from the measured value of $|\epsilon_K|$ gives the New Physics contribution, $|\epsilon_K^{\rm NP}| = |{\rm Im}[M_{12}^{\rm NP}(K)]|/(\sqrt{2}\Delta m_K)$.

In Figure 6 we show the New Physics contribution to $|\epsilon_K|$ as a function of γ, for both present-day and more long-term uncertainties on B_K and $|V_{ub}/V_{cb}|$. It is evident that a measurement of γ is the key ingredient needed to answer the question of whether or not there is New Physics in K–$\bar{K}$ mixing. Once γ is known, $|{\rm Im}[M_{12}^{\rm NP}(K)]|$ can be extracted with good precision.

4 New Physics in decays

In order for a reference triangle construction to give the true value of γ, and thus be useful for extracting potential New Physics contributions to the mixing amplitudes, it must not be contaminated by additional New Physics effects in the associated decay amplitudes. Up to now we have assumed consistency between the different constructions, which would imply that to a good approximation New Physics enters only in the mixing amplitudes. This is indeed the case in many extensions of the Standard Model, particularly if the scale of new flavor interactions is at a TeV or beyond. Of course, it would be extremely exciting if the different reference triangle constructions were *not* consistent with one another, implying that there is New Physics in B decay amplitudes, or that the 3-generation CKM matrix is not unitary.

In Section 2 we have discussed various reference triangle constructions in roughly the chronological order in which it will be possible to carry them out. Interestingly, this order also corresponds to a progression from reliance on decays which in the Standard Model are penguin-dominated (and therefore more susceptible to New Physics) to those which are tree-dominated (and therefore less susceptible to New Physics), and finally to decays that are only based on tree topologies.

We briefly discuss tests for New Physics contributions to the penguin-dominated decays based on $b \to s\bar{q}q$ transitions in the Standard Model. These tests can be carried out at various stages of data collection. The measurement of several CP-averaged $B \to \pi K$ and $B \to \pi\pi$ decay rates itself provides for a series of internal consistency checks. For instance, there are upper and lower bounds on certain rate ratios, which are based on flavor symmetries and rely on minimal theoretical input. Violation of these bounds would be a signal for new isospin-violating New Physics contributions [19]. In the longer term, as measurements of CP asymmetries for rare decays become available, additional tests will become possible. For example, one can then check whether the time-dependent CP asymmetries in $B \to J/\Psi\, K_S$ and $B \to \phi K_S$ decays are in agreement. A discrepancy would imply new CP-violating contributions to the $B \to \phi K_S$ decay amplitude, which to a good approximation is a pure $b \to s\bar{s}s$ penguin amplitude in the Standard Model [20]. There are

also upper bounds on the direct CP asymmetries for $B^\pm \to \pi^\pm K^0$ and $B^\pm \to \phi K^\pm$ in the Standard Model, which could turn out to be violated [21,22]. Finally, a large direct CP asymmetry in $B^\pm \to X_s\gamma$ decays would imply significant New Physics contributions to $b \to s$ penguin transitions [23].

If all penguin-dominated determinations of γ are consistent, then it is unlikely that there is New Physics in decays, and the program we have outlined above for extracting New Physics in mixing can already be carried out with confidence. If these determinations are not all consistent, however, the tree-dominated or pure tree reference triangle constructions will be required in order to reliably extract New Physics contributions to mixing. (At the same time, a clean determination of γ would be be required in order to obtain a detailed picture of the New Physics in the penguin-dominated decays [19].) The determination of γ from the mixing-induced CP asymmetry in $B \to \pi^+\pi^-$ is less susceptible to New Physics effects, since these would have to compete with a Cabibbo-enhanced tree-level amplitude. Finally, the extractions of γ from the pure tree processes $B \to D^{(*)}\pi$ and $B \to DK$ can only be affected by New Physics in rather exotic scenarios. Thus, checking for consistency between these two measurements and the $B \to \pi^+\pi^-$ measurements essentially provides a test for New Physics effects in $B \to \pi\pi$.

If dedicated experiments to study the very rare $K \to \pi\nu\bar{\nu}$ decay modes will be performed, they will provide direct measurements of the magnitude and phase of V_{td} independent of mixing. The comparison of the kaon reference triangle with the triangles obtained from B decays primarily allows us to probe for New Physics in these rare kaon decays, which in the Standard Model are mediated by box and electroweak penguin diagrams. In addition, if the kaon and B-mesons triangles were to agree with one another, this would be a direct test of the assumption of 3-generation CKM unitarity, as it would check the relation $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$ independent of any mixing measurements. Another test of CKM unitarity would be the direct measurement of the element $|V_{tb}|$ (and perhaps $|V_{ts}|$) in top decay.

5 Conclusions

Motivated by today's announcement of the first $\sin 2\beta_{\psi K}$ measurements from the dedicated B-factory experiments BaBar and Belle, we have reconsidered strategies for exploring New Physics in B–$\bar{B}$ and K–$\bar{K}$ mixing in a model-independent way. The low central values found by these experiments raise the possibility that there is New Physics in B_d–$\bar{B}_d$ mixing. Therefore it becomes crucial to base studies of flavor physics on comparisons with a reference unitarity triangle whose construction is independent of mixing measurements. Ultimately, such a strategy is preferable whether or not the measured value of $\sin 2\beta_{\psi K}$ agrees with the prediction from the global analysis of the unitarity triangle.

We have described in detail a program that in a few years could cleanly determine the New Physics contributions (in magnitude and phase) to the B_d–$\bar{B}_d$ and K–$\bar{K}$ mixing amplitudes. (A similar, more straightforward analysis for B_s–$\bar{B}_s$ mixing can be performed at the BTeV and LHCb experiments.) Similar strategies have been proposed previously by several authors. Here we have stressed the relevance of the progress recently made in devising strategies for near-term measurements of the weak phase γ based on charmless hadronic B decays. Knowing γ with reasonable accuracy, and without discrete ambiguities, is *the* key element that makes the program outlined in this Letter feasible and very powerful. We have also pointed out that the comparison of different constructions of the reference triangle provides several opportunities for probing New Physics in decay amplitudes, not related to mixing. Nothing would be more exciting than to follow the unfolding of New Physics at the B factories in the next few years ahead of us.

Acknowledgements: We wish to thank the SLAC Theory Group for its hospitality while this work was carried out. A.K. is supported by the Department of Energy under Grant No. DE-FG02-84ER40153. M.N. is supported in part by the National Science Foundation.

References

1. Plenary talks presented by D. Hitlin (BaBar Collaboration) and H. Aihara (Belle Collaboration) at ICHEP2000, Osaka, Japan, 31 July 2000 (to appear in the Proceedings).
2. T. Affolder et al. (CDF Collaboration), *Phys. Rev. D* **61**, 072005 (2000).
3. F. Caravaglios, F. Parodi, P. Roudeau and A. Stocchi, `hep-ph/0002171`.
4. G. Bonvicini et al. (CLEO Collaboration), *Phys. Rev. Lett.* **84**, 5940 (2000).
5. T. Goto, N. Kitazawa, Y. Okada and M. Tanaka, *Phys. Rev. D* **53**, 6662 (1996).
6. A.G. Cohen, D.B. Kaplan, F. Lepeintre and A.E. Nelson, *Phys. Rev. Lett.* **78**, 2300 (1997).
7. Y. Grossman, Y. Nir and M.P. Worah, *Phys. Lett. B* **407**, 307 (1997).
8. G. Barenboim, G. Eyal and Y. Nir, *Phys. Rev. Lett.* **83**, 4486 (1999).
9. M.B. Voloshin, *Mod. Phys. Lett. A* **12**, 1823 (1997).
10. M. Neubert, *Nucl. Phys. (Proc. Suppl.)* **86**, 477 (2000).
11. M. Beneke, G. Buchalla, M. Neubert and C.T. Sachrajda, *Phys. Rev. Lett.* **83**, 1914 (1999); `hep-ph/0006124`.
12. M. Beneke, G. Buchalla, M. Neubert and C.T. Sachrajda, `hep-ph/0007256`.
13. M. Neubert and J.L. Rosner, *Phys. Rev. Lett.* **81**, 5076 (1998);
    M. Neubert, *JHEP* **02**, 014 (1999).
14. A.E. Snyder and H.R. Quinn, *Phys. Rev. D* **48**, 2139 (1993).
15. I. Dunietz and R.G. Sachs, *Phys. Rev. D* **37**, 3186 (1988) [Erratum: *ibid.* **39**, 3515 (1989)];
    I. Dunietz, *Phys. Lett. B* **427**, 179 (1998).
16. D. Atwood, I. Dunietz and A. Soni, *Phys. Rev. Lett.* **78**, 3257 (1997).
17. For a review, see: *B Decays at the LHC*, P. Ball et al. (convenors), `hep-ph/0003238`.
18. For a review, see: G. Buchalla, A.J. Buras and M.E. Lautenbacher, *Rev. Mod. Phys.* **68**, 1125 (1996).
19. Y. Grossman, A.L. Kagan and M. Neubert, *JHEP* **10**, 029 (1999).
20. Y. Grossman and M.P. Worah, *Phys. Lett. B* **395**, 241 (1997).
21. A.J. Buras, R. Fleischer and T. Mannel, *Nucl. Phys. B* **533**, 3 (1998).
22. A.F. Falk, A.L. Kagan, Y. Nir and A.A. Petrov, *Phys. Rev. D* **57**, 4290 (1998).
23. A.L. Kagan and M. Neubert, *Phys. Rev. D* **58**, 094012 (1998).